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Current Los Alamos Sferic Array Studies

Matthew J Heavner, David A Smith, and Jeremiah Harlin

Los Alamos National Laboratory

Abstract. An array of fast electric-field-change sensors has been operated in New Mexico, Texas, Florida, and Nebraska during 1998-2000 to improve identification of lightning processes responsible for VHF and optical signals detected by the FORTE satellite. Differential time of arrival methods are used to provide geo-locations of events from multi-station observations. A comparison of two dimensional location from the sferic array and the National Lightning Detection Network operated by Global Atmospherics, Inc. is presented. Also, the time differences of multiple paths of the lightning signals to a station due to ionospheric reflection can be used to determine the altitude of a temporally narrow event. We present altitude determination of Compact Intracloud Discharges observed by the sferic array and compare with the Kennedy Space Center Lightning Detection and Ranging (LDAR) system in Florida.

Introduction

The FORTE satellite was launched Aug. 1997 with instrumentation capable of making both Very High Frequency (VHF) and optical observations of lightning. In order to characterize the FORTE observations, the Los Alamos Sferic Array (LASA) began operation in 1998 as an array of five Very Low Frequency (VLF) electric field change meters in New Mexico to study thunderstorms in support of FORTE satellite-based lightning research. LASA/FORTE comparisons have been fruitful [Massey *et al.*, 1998a]. To study a large number of coincident observations of ground based and FORTE observations of lightning, the National Lightning Detection Network (NLDN) has been used for FORTE comparisons [Jacobson *et al.*, 2000]. One surprising result of the FORTE/NLDN comparison is a coincident event detection rate of only $\sim 1\%$ when FORTE is overhead the NLDN (personal comm., A. Jacobson). In order to understand the low FORTE/NLDN rate of coincidence, further VLF/VHF comparisons are being undertaken.

This paper presents comparison between LASA and the National Lightning Detection Network (NLDN) in order to characterize the location accuracy of LASA. This paper also describes the preliminary comparison between LASA and the Kennedy Space Center Lightning Detection and Ranging (LDAR) system. As of 1999, LASA and LDAR are co-located, and LDAR is a VHF system roughly similar to the VHF observations of FORTE.

Sferics

The transient electrical activity of thunderstorms (primarily return and intracloud activity) generates electromagnetic (EM) radiation events known as sferics. A typical return stroke produces radiation peaking at $\sim$10 kHz while typical intracloud stroke produces radiation peaking at a slightly higher frequency (at $\sim$40 kHz) with 2 orders of magnitude less energy than a typical return stroke [Volland, 1995]. EM radiation at these frequencies propagates through the earth-ionosphere waveguide, so can be observed at large distances (greater than 2000 km) from the source.

Los Alamos Sferic Array

LASA is a classic electric field change meter [Krehbiel *et al.*, 1979], with the added ability to derive accurate, absolute time tags at multiple, distant locations using Global Positioning System (GPS) receivers. The GPS receiver provides absolute event time tagging with an accuracy of better than 2 μs. The multistation coincident waveforms were cross-correlated to determine timing corrections between events recorded by different stations and also to reject waveforms which originate from different sources. Smith *et al.* [2000] describe the operation and instrumentation of LASA in more detail.

The LASA operation began with five stations (only four of which were independently located) in New Mexico in 1998. The stations were located in Los Alamos (LO and LA), Socorro (SO), Roswell (RO), and

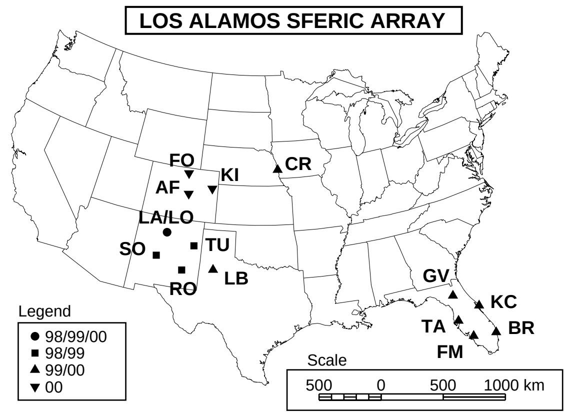

Figure 1. Los Alamos Sferic Array station locations for 1998, 1999, and 2000.

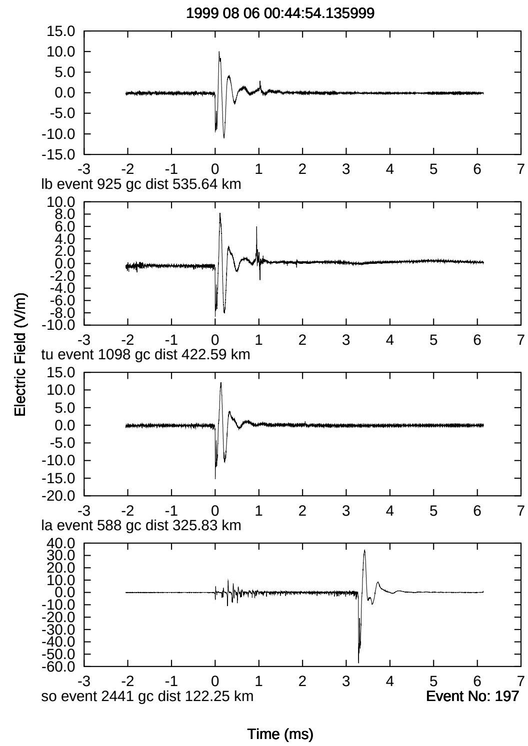

Figure 2. Field change waveforms from a negative cloud-to-ground lightning return stroke that occurred 24 km southwest of Los Alamos at 00:44:54.132599 UTC on August 8, 1999. The Socorro station (closest to the event) triggered on leader radiation.

Tucumcari (TU). In 1999 the array was expanded to eleven stations (all independently located) with the four stations in New Mexico; one in Omaha, Nebraska (CR); one in Lubbock, Texas (LB); and five in Florida: Kennedy Space Center (KC), Tampa (TA), Fort Myers (FM), Boca Raton (BR), and Gainesville (GV). For 2000 summer operations, the SO, RO, and TU NM array stations were relocated to Colorado: Colorado Springs (AF), Fort Collins (FO), and Kirk (KI), in order to make comparative observations with the New Mexico Tech Lightning Mapping Array (LMA), a VHF system described below, and other instruments associated with the STEPS campaign [Weisman and Miller, 2000]. Fig. 1 presents maps of the LASA station locations.

The primary goal for 1998 was to support FORTE and gain experience in the remote operation of an array through the establishment of stations close to Los Alamos. The locations also allowed comparative observations with the New Mexico Tech LMA, a VHF system operated in the vicinity of Socorro.

In 1999, utilizing the two-cluster array plus the independent station in NE, high sensitivity, high location accuracy studies within and near each sub-array were possible, and the array was simultaneously able to detect and locate (with less accuracy) large-amplitude events that occurred over a large portion of the southern and central U. S. The expansion to Florida in 1999 was motivated by the following factors: (1) the Florida peninsula features the highest flash density in the Unites States [Cummins *et al.*, 1998b]; (2) the opportunity for thunderstorm observations in a maritime environment; (3) and colocation with the LDAR system at KSC, a VHF system described below.

LASA was developed as a resource to locate, classify, and characterize lightning discharges in support of FORTE, in a manner similar to NLDN. One advantage of operating our own ground-based array is that we are able tailor operations for coordination with FORTE. A second advantage is the ability to retain all waveforms from all located events to permit further, non-real-time analysis. As we have advanced our understanding of lightning and developed new questions, the ability to reprocess these waveform data has been critical. The array has the potential to contribute to the understanding of thunderstorm discharges independent of FORTE, and has already begun to do so.

Fig. 2 shows typical waveforms recorded from a negative cloud-to-ground lightning stroke (59 kA peak current as reported by the NLDN) that occurred August 6, 1999 at 00:44:54.135999 near the New Mexico array and was recorded by the LB, TU, LA, and SO stations. The SO waveform shows leader radiation which caused the station to trigger and record the event (in this plot t=0 corresponds to the trigger time, rather than the cross-correlation corrected event time).

FORTE description

The FORTE satellite was launched August 1997 into a 70° inclination orbit at 825 km altitude. Scientific instrumentation aboard the satellite includes both radio frequency (RF) and optical packages. The primary FORTE research payload includes two 20 MHz-bandwidth RF receivers, a 100 MHz-bandwidth RF receiver, an optical imager, and an optical photodiode detector. These instruments regularly record the radio and optical emissions from terrestrial lightning discharges. FORTE RF payloads and observations have been described by Massey *et al.* [1998b]; Jacobson *et al.* [1999]; Suszcynsky *et al.* [2000b]. The optical payloads, observations, and modeling have been described by Light *et al.* [2000]; Suszcynsky *et al.* [2000b, a].

A significant portion of the FORTE science effort has focused on the merging FORTE RF and optical observations with those from other satellite-based and ground-based resources. This data fusion has enhanced the value of FORTE observations in at least three respects: 1. Sensors with the ability to accurately geolocate sources have provided locations for events that FORTE has recorded but been unable to locate (FORTE's limited geolocation capabilities have been described by Suszcynsky *et al.* [2000a]; Jacobson *et al.* [1999] and Jacobson and Shao [2000]; 2. Multiple characterizations of the same stroke, flash, or storm using different sensor types have provided insight into thunderstorm electrification and discharge processes that no single sensor has been able to provide; 3. Sensors capable of continuously observing storms have provided a context for FORTE data collection, which is limited to the observation of a single point on the ground for only fifteen minutes (at most) per 100-minute orbit. One surprising result of the current FORTE/NLDN comparison is a coincident event detection rate of only ~1% when FORTE is overhead the NLDN (personal comm., A. Jacobson). In order to understand the low FORTE/NLDN coincidence rates, further VLF/VHF comparisons are being undertaken using LASA as a system similar to NLDN, but providing complete waveform information as an improvement over the parameterization of waveforms provided by NLDN, and LDAR or LMA VHF systems.

NLDN description

The National Lightning Detection Network (NLDN) is comprised of 59 LPATS-III time-of-arrival sensors and 47 IMPACT sensors that provide both time-of-arrival and direction-finding information. The NLDN sensors are responsive to VLF EM radiation (similar to the LASA response), sensing the radiation associated with return strokes and intracloud strokes. In addition to generally weaker radiation from intracloud strokes, the NLDN processing is designed to filter against intracloud activity. This network of sensors provides primarily cloud-to-ground lightning detection across the coterminous United States (CONUS).

The NLDN data sets used for the comparisons were not standard NLDN data products, but were reprocessed from raw data using relaxed event criteria ('loosened criteria') to maximize detection of intracloud discharges and distant/weak cloud-to-ground discharges. The 1999 data were processed with somewhat more strict criteria than the 1998 data. The standard NLDN data provide 80-90% detection efficiency of cloud-to-ground strokes with currents of greater than 5 kA within the CONUS. These events are located with an accuracy of 500 m [Cummins *et al.*, 1998a]. The 'loosened criteria' data used for comparison in this paper may not meet these quality-control criteria. Their uncertainty has not been characterized.

LDAR and LMA description

The Lightning Detection and Ranging (LDAR), located at Kennedy Space Center, is a network of sensors tuned to locate the impulsive 66 MHz (VHF) radiation emitted by lightning channel processes [Poehler and Lennon, 1979; Lennon and Maier, 1991]. The network consists of six antennas spaced 6-10 km away from one central antenna. Multiple station observations are used for time-of-arrival location of VHF radiation sources. Based on climatological studies of the LDAR system, Boccippio *et al.* [2000a] find that the LDAR bulk flash detection efficiency is above 90% to 94-113 km range and falls below 10% at ranges greater than 200-240 km.

The New Mexico Tech Lightning Mapping Array (LMA) is a deployable systems to locate VHF lightning radiation based on the LDAR system described above. The LMA makes use of GPS technology to independently measure the arrival time of radiation at several (10+) stations which detect the peak intensity of VHF radiation in the 6 MHz bandwidth centered at 63 MHz. Rison *et al.* [1999] describe both the LMA system and joint LASA/LMA observations of narrow bipolar pulses that were made during 1998.

Compact Intracloud Discharges

Narrow bipolar electric field change pulses (NBEs) associated with powerful RF radiation have previously been described by several researchers [LeVine, 1980; Willett *et al.*, 1989; Smith, 1998; Smith *et al.*, 1999; Rison *et al.*, 1999]. Smith *et al.* [1999] showed that the discharges occur in clouds and stated that the sources, referred to as compact intracloud discharges (CIDs), emit distinct fast and isolated bipolar electric field change signatures. CIDs are excellent targets for FORTE, which regularly records RF radiation from CIDs in the form of transionospheric pulse pairs [Holden *et al.*, 1995; Massey and Holden, 1995].

Fig. 3 shows a LASA example of multiple-station narrow negative bipolar pulse (NNBP) recorded by the New Mexico TU, RO, LA, and SO stations on July 8, 1998 from distances of 388, 544, 607, and 702 km respectively. The event occurred in Oklahoma east of the Texas Panhandle. The pulse is so temporally narrow that it is not possible to determine the polarity of the pulse from the plots of the entire 8 ms record. Depend-

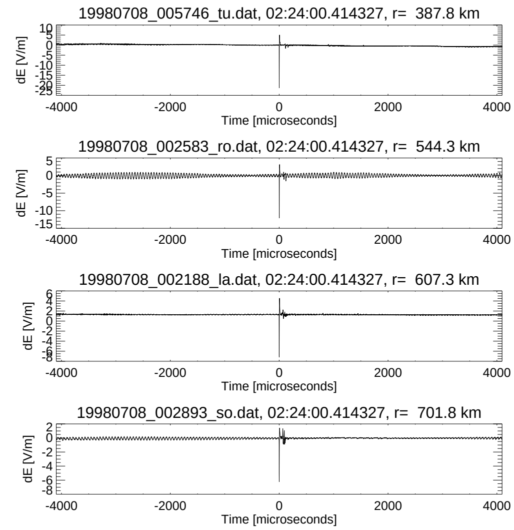

Figure 3. Field change waveforms from a narrow negative bipolar pulse recorded by the New Mexico TU, RO, LA, and SO stations on July 8, 1998 at 02:24:00.414327. The ionospheric reflections of the signal can be seen in the waveforms of all four stations.

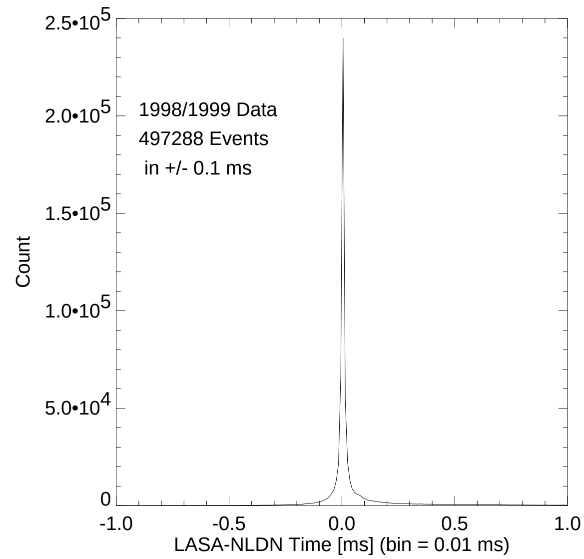

Figure 5. Histogram of LASA/NLDN time differences. The sharp peak centered at a time difference of 0 strongly indicates that the two systems are observing the same source.

ing on the source/receiver distance, ionospheric reflection may provide multiple pulses in the NBE waveforms due to the different travel times of the multiple paths for the VLF signal from lightning to a single LASA station. This is illustrated in Fig 4. The multiple paths allow the determination of both the source height and the reflecting ionospheric height. Ionospheric reflections are visible in all three waveforms immediately following the groundwave signal. The three dimensional source location of the CIDs is routinely determined for NBEs observed by LASA.

Among the distinguishing characteristics of NBEs are their fast rise and fall times and their isolation within our 8 ms duration electric field change records. Indications of intracloud activity are occasionally observed in the 8 ms LASA records.

This paper describes a comparison between LASA and the National Lightning Detection Network (NLDN) in order to characterize the accuracy of LASA geolocations. Also, initial results of a comparative study between LASA and the Kennedy Space Center LDAR are presented.

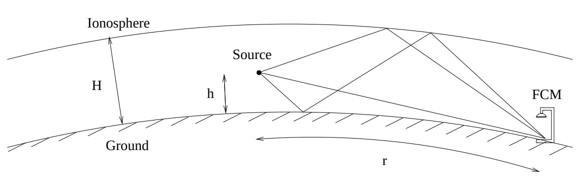

Figure 4. Depiction of the source-receiver geometry leading to multiple paths for the VLF radiation from lightning.

Results

The comparison between the LASA and NLDN systems is used to derive estimates of the accuracy of LASA. Both the LASA/NLDN and an initial comparison between the LASA and LDAR systems are described in the section.

LASA geolocation accuracy

Time-of-arrival lightning location systems, using low-frequency and high-frequency detection systems, have been described and utilized by many researchers [Cummins *et al.*, 1998a; Smith *et al.*, 1999; Rison *et al.*, 1999]. Limits on the accuracy and precision of such systems depend fundamentally upon the accuracy and precision of the absolute timing source or sources that are used to time tag events at each station. Based on instrumental tests, the LASA 2 μs timing uncertainty corresponds to an optimal location uncertainty of 600 m.

To evaluate the location accuracy of the sferic array we compared LASA event locations to lightning locations determined by the National Lightning Detection Network (NLDN) for Apr.-Sep. 1998 and May-Oct. 1999. The LASA/NLDN comparison was begun by identifying all 1998 and 1999 temporal coincidences between the two data sets within a $\pm$ 20 ms window. Fig. 5 shows the LASA/NLDN time coincidence histogram over a range of $\pm$1 ms with a bin size of 10 μs.

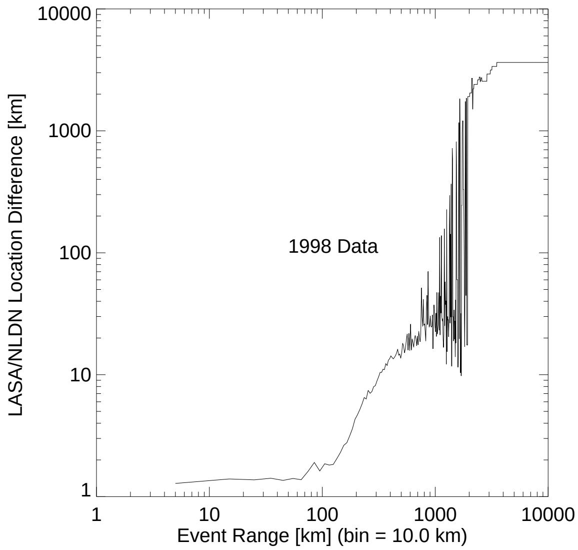

Figure 6. Log-log plot of LASA/NLDN location differences as a function of LASA event range from the center of the NM array.

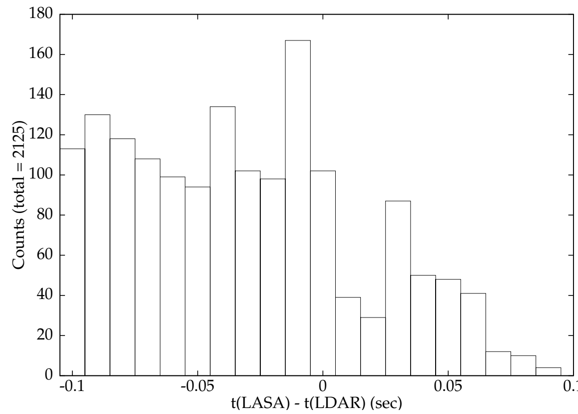

Figure 7. Histogram of LASA/LDAR CID time differences in a ±100 ms window. The LASA system and LDAR system appear to be observing the same initial burst of radiation from a CID.

The peak is well defined, with a half width of 7 μs (determined separately with finer binning).

Based on Fig. 5, the time coincidence window for the location analysis was selected to be ±100 μs. The number of events within this window was 497,288. The number within the original ±20 ms window was 813,064. The cumulative distribution of spatial separations between the LASA and NLDN event locations for events within the ±100 μs coincidence window shows that for the entire 1998/1999 database, 38% of the LASA/NLDN temporal coincidences agree to within 1 km, 85% to within 10 km, 99% to within 40 km, and 99.9% to within 220 km. Further analysis will address only the 1998 data because of the simpler array geometry (the stations nearly formed a square as seen in Fig. 1). The results for the 1998-only database were that 45% of the coincidences agree to within 1 km, 88% to within 10 km, 99% to within 40 km, and 99.9% to within 220 km. From these data alone it does not appear that LASA approaches the theoretical best location accuracy of 600 m.

Location accuracy on an event-by-event basis is addressed in Fig. 6, a log-log plot of the average LASA/NLDN location difference as a function of range from the NM array centroid. The figure shows that on average the event locations agree to within 1.3 km out to 70 km from the center of the NM array. They agree to within 2.0 km out to a distance of 130 km, a range that corresponds to the edge of the NM array. Beyond this distance the location difference decays somewhat linearly to a range of 1000 km where the mean LASA/NLDN location difference is 25 km.

LDAR

As indicated previously, one reason for the 1999 Florida expansion of LASA was colocation with the Kennedy Space Center LDAR system, using the LDAR system as a ground based VHF system similar to FORTE. Initial comparison of LASA/LDAR observations has been performed on VLF NBE observations from LASA compared with VHF observations from LDAR. As with the NLDN results presented above, the initial step in the analysis was a comparison of the temporal identification of sources, in order to determine that the two systems are indeed observing the same phenomena. The histogram of time differences for over 2000 CIDs observed by LASA compared with LDAR observations is presented in Fig. 7. The LASA/NLDN histogram in Fig. 5 shows a maximum time separation of ±1 ms, while the LASA/LDAR histogram in Fig. 7 shows ±100 ms. The LDAR system records $\sim$100 VHF events for each LASA event, and based on the histogram, the two systems are not necessarily observing the same phenomena at more than a gross level. The LASA/LDAR histogram indicates that LASA is triggering on the initial burst of VLF radiation associated with CIDs, while LDAR sees that intial radiation followed by more events within 100 ms (possibly intracloud activity associated with the CID).

Taking the LDAR event temporally closest to the LASA NBE event, the height reported by each system is plotted in Fig. 8. The dashed line indicates a perfect agreement between the two systems. The LASA/LDAR CIDs identified for this study are all negative polarity NBEs (NNBEs), and agree with the altitude of FORTE/LASA NNBEs.

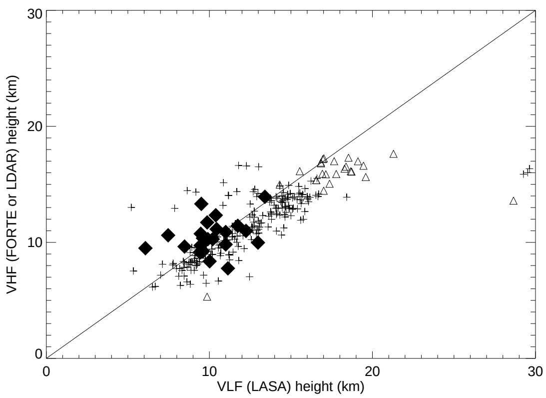

Figure 8. Height comparison of VHF/VLF CID event locations. The '+' symbol is the FORTE/LASA positive CID altitude comparison, the triangles are the FORTE/LASA negative CID altitude comparison, and the solid diamonds are the LDAR/LASA CID altitude comparison (all LDAR/LASA events were negative polarity. The line is plotted to illustrate a perfect agreement of the altitude determination betwee the VHF and VLF systems.

Discussion

This paper presents two main points: the LASA/NLDN comparison for the determination of the LASA accuracy, and the intial LASA/LDAR comparison in order to understand the low event coincidence rate between NLDN and FORTE.

The theoretical 600 m location accuracy was postulated under conditions of favorable geometry and assuming an excellent waveform cross correlation capability. Despite the favorable geometry within the 1998 New Mexico array, as illustrated in Fig. 6, the optimal predicted accuracy of 600 m was not achieved. This may be attributed to several factors: the first is the fact that the NLDN lightning locations do not necessarily represent the true source locations. The uncertainty for the standard NLDN data product is 0.5 km. It is not known whether this accuracy is achieved for the region of New Mexico that includes the 1998 LASA stations. The effect of NLDN 'loosened criteria' (explained earlier) is also not known. A second consideration is that LASA waveform cross correlations are not perfect. With identical waveforms at all stations it would be possible to determine the actual DTOAs to within 1 μs. Propagation over the finitely conducting ground, ionospheric reflections, and static-near and inductive-intermediate field influences all affect the wave shapes. Some of these effects are illustrated by the waveforms in Fig. 2. A third source of contamination is from incidental coincidences. The events used for this comparative study were selected by finding ± 100 μs LASA/NLDN coincidences. Event ranges from the NM array centroid were based on the LASA event locations. Incidental NLDN events that occurred within the ± 100 μs window with LASA events, but occurred at great distances could be included in Fig. 6. Within the sub-arrays, the LASA geolocation error is comparable to the reported NLDN errors.

A surprising result of the FORTE/NLDN comparison is a coincident event detection rate of only $\sim 1\%$ (personal comm., A. Jacobson). In order to understand the low FORTE/NLDN coincidence, further VLF/VHF comparisons are currently underway, using LASA (VLF) and co-located ground VHF systems in order to collect more VLF information than provided by NLDN (waveforms, rather than waveform parameters) and also to increase the number of VLF/VHF coincidences (compared to FORTE/LASA[1]). The LASA/LDAR results presented illustrates one of the most difficult aspects of VLF/VHF comparisons–namely, the large number of VHF events reported for each VLF event ($\sim$100 for the LASA/LDAR comparison). One solution taken by other investigators comparing LDAR with other systems is to group the LDAR events and do a climatological study rather than an event-based study [Boccippio *et al.*, 2000b, *e.g.*]. Currently we are examining methods of making an event-based comparison between LASA and VHF systems (LDAR and LMA).

Conclusion

The 2-D location uncertainty for 80 % of the events located by LASA (those occurring closest to station clusters in NM and FL) was better than 2 km, as determined through comparison with data from NLDN. The Florida result was not proven, but the argument is made based on the similar (or even shorter) baselines and the better propagation conditions in Florida. Within an array diameter of each sub-array, it appears to be reasonable to expect location accuracy on the order of or better than 10 km. Beyond this distance, the accuracies degrade steadily with distance when the members of the sub-array are the only participants in the location determination. Not addressed in this analysis were events detected by members of more than one sub-array and/or by the CR station.

The initial results of the LASA/LDAR reveal both the dissimilarities in the two data sets (with almost 100 LDAR events per one LASA event on average) and also indications of an underlying commonality in the data. Current research efforts are directed at extending the initial LASA/LDAR research presented in this paper.

Acknowledgments. The authors wish to acknowledge the significant accomplishments of our friend and coworker Robert (Bob) Massey, who passed away suddenly on March 5th of 1999. He was a brilliant and funny man who had a

[1]There were $\sim$2400 FORTE/LASA coincidences in 1998-1999.

tremendous positive influence on those who knew him. He is dearly missed. K Cummins of Global Atmospherics provided the NLDN data used in this study. Furthermore, we thank the following individuals and institutions who have hosted LANL Sferic Array stations: T Hamlin, P Krehbiel, B Rison, M Stanley, and R Thomas of NM Tech; R Griego, J King, D Klassen, and H Pleasant of Eastern NM Univ.; J Morgan of Mesa Tech. College; D Morss and B Strabley of Creighton Univ.; M Brooks, J Madura, and F Merceret of NASA KSC; R Chang, D Rabson, and D Spurgin of the Univ. of South FL; Walter, Leslie, and Cheryl Peterson of Cyberstreet in Fort Myers; P Hackett, T Kelly, S Morgera, V Ungvichian, and H Vansant of FL Atlantic Univ.; J Goetten, V Rakov, K Rambo, and M Uman of the Univ. of FL; S Patterson and T Trost of Texas Tech Univ.; G McHarg, K Broome, and D Vititoe of the U.S. Air Force Academy; R Olson of Plains Network; J Fulton of Plains Telephone; and W Petersen, S Rutledge, and W Naylor of Colorado State Univ.. LANL personnel who also made significant contributions include A Jacobson, M Carter, D Roussel-Dupré, M Pongratz, and M Eberle. The enthusiastic support of all of these people made its success possible. This work was performed under the auspices of the United States Department of Energy. M. Heavner acknowledges many fruitful discussions with C. Talus.

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MJ Heavner and DA Smith, Space and Atmospheric Sciences Group, NIS-1, MS D466, Los Alamos National Laboratory, Los Alamos NM 87545. [heavner,smithda]@lanl.gov

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